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INVESTIGATION OF PURE TONES GENERATED BY ORIFICES

Report No 89-103-K

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ABSTRACT

This report describes a series of tests on various orifice configurations and arrangements in a piping system under various combinations of temperatures and flowrates. The aim is to determine the conditions for the generation of pure tones which can cause excessive vibration of piping components. This work contributes directly towards the understanding and development of solutions for the tone-excited vibration problem in the ROH Balance line at Darlington NGS. A new orifice configuration is proposed which has the potential to obviate tone generation under any operating condition.

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27-024-100	825.5	June 14, 1989	89-103-K

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EXECUTIVE SUMMARY

INVESTIGATION OF PURE TONES GENERATED BY ORIFICES

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As a result of the vibration problem in the ROH Balance line at Darlington NGS, a parametric study of pure tones produced by orifices was conducted in a high temperature and pressure flow loop at NPCTF, covering ten orifice configurations and various combinations of temperature and flowrate. The acoustic intensity technique was used to identify and measure the flow of acoustic energy from the source of the excitation.

Results indicate that a standard orifice can be a strong acoustic source in response to the acoustics of the associated piping system. The generated pure tones may be completely eliminated by changing the shape of orifice opening while maintaining the same loss coefficient. In particular, a novel notched orifice of the same opening area as a standard orifice has been found to completely eliminate pure tones under all combinations of orifice location, flowrate and temperature.

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TABLE OF CONTENTS

		Page
1.0	Introduction	1
2.0	Description of Flow Loop and Orifice Configurations	2
3.0	Description of Test Location and Measurement Techniques	2
4.0	Test Procedure and Results	3
	4.1 Configuration 1 --- Standard Orifice at Reference Location	3
	4.2 Configuration 2 --- Double Orifice at Reference Location	4
	4.3 Configuration 3 --- Standard Orifice Upstream of Reference Location	4
	4.4 Configuration 4 --- Standard Orifice Downstream of Reference Location	4
	4.5 Further Discussion of Results, Configurations 1 to 4	4
	4.6 Configurations 5 and 6 --- Orifice with 16 Notches	5
	4.7 Configurations 7 and 8 --- Orifice with 2 and 4 Notches	5
	4.8 Configuration 9 --- Orifice with Offset Opening	5
	4.9 Configuration 10 --- Orifice with Multiple Opening	5
	4.10 Comparison with Darlington Results	6
5.0	Conclusions and Recommendations	6
	REFERENCES	
	FIGURES 1 - 16	
	DISTRIBUTION	last page

LIST OF FIGURES

1. GENERAL LAYOUT OF FLOW LOOP
2. PICTURE OF FLOW LOOP AT ORIFICE LOCATION
3. SUMMARY OF ORIFICE CONFIGURATIONS
4. VARIATION OF WAVE SPEED WITH TEMPERATURE
5. SUMMARY OF PURE TONES OBSERVED UNDER VARIOUS CONDITIONS
6. PRESSURE FLUCTUATION, CONFIGURATION 1, 90 DEGREES C
7. ACOUSTIC INTENSITY, CONFIGURATION 1, 90 DEGREES C
8. VIBRATION VELOCITY, CONFIGURATION 1, 90 DEGREES C
9. PRESSURE FLUCTUATION, CONFIGURATION 1, 130 DEGREES C
10. ACOUSTIC INTENSITY, CONFIGURATION 1, 130 DEGREES C
11. PRESSURE FLUCTUATION, CONFIGURATION 1, 220 DEGREES C
12. ACOUSTIC INTENSITY, CONFIGURATION 1, 220 DEGREES C
13. PRESSURE FLUCTUATION, CONFIGURATION 1, 260 DEGREES C
14. ACOUSTIC INTENSITY, CONFIGURATION 1, 260 DEGREES C
15. COMPARISON OF PRESSURE LOSS ACROSS ORIFICES
16. TYPICAL RESULTS FROM DARLINGTON BALANCE LINE L-31

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To Mr. G. Childerhose
Production Manager
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INVESTIGATION OF PURE TONES GENERATED BY ORIFICES

1.0 INTRODUCTION

This parametric study was funded jointly by Darlington Operations and Mechanical Research to investigate the conditions leading to the generation of pure tones by an orifice in piping systems. Although this work was initiated as a result of a vibration problem occurring on a ROH balance line at Darlington NGS, use was made of an existing flow loop which was set up for a previous orifice test for the stability line at Point Lepreau/1/.

The balance line (L31) situation at Darlington NGS, Unit 2, can be summarized as follows. This is a '10-inch' line with an orifice of 67.7 mm diameter opening. During early commissioning tests, a pure tone vibration at around 400 Hz was induced under the two-pump operation condition. This unbalanced condition led to the maximum pressure differential between the two outlet headers and, therefore, a high flowrate through the line. Failures of attached branch lines occurred after short periods of operation due to the induced vibration. The subsequent increase in diameter of the opening of the orifice to 90 mm reduced the incidence of occurrence of the tone to certain temperatures and flowrates. However, the tone still occurred.

The latest modification involved a further increase of the orifice opening diameter to 93.4 mm and the tone was not induced under any tested conditions. It should be noted that throughout the commissioning tests, light water was used, the reactor of Unit 2 was not fuelled and the operating temperature was below 260°C. Significantly higher flowrates and over 300°C are expected during normal plant operation. There is a concern as to whether the tone would appear again under those conditions and what subsequent measures could be taken, bearing in mind that the loss coefficient is already at the low end of the design range.

The flow loop for the previous Point Lepreau orifice tests was chosen because pure tones were produced in that study and the loop provided flexibility in terms of choice of orifice location, flowrate and temperature. The nature of the tones in that study was similar to that at Darlington NGS in terms of their magnitudes, their 'purity' and their sensitivity towards small changes in operating conditions.

2.0 DESCRIPTION OF FLOW LOOP AND ORIFICE CONFIGURATIONS

The general layout of the flow loop is shown in Figure 1. Water for the loop is supplied from an existing '16-inch' line connected to the discharge of the main pump in the NPCTF. The loop consists of an '8-inch' gate valve which allows flowrate adjustment, '6-inch' Sch 120 piping, a spool piece with an orifice at its middle, three flanged couplings where orifice plates may be installed, and an abrupt expansion into an existing '16-inch' line which is connected to the suction of the main pump. Figure 2 shows a view of part of the loop at the orifice location.

The ten orifice configurations in this study involve variations of the geometry of the orifice opening and the location of the orifice within the loop. A summary of the configurations is shown in Figure 3. They are numbered according to the order in which they were tested. Configurations 1, 3 and 4 involve the 'standard' orifice which has an opening of 69.6 mm diameter. They differ in the location of the orifice. Configuration 2 involves a double orifice with its mean position the same as that of the standard orifice in Configuration 1. The double orifice proved to be effective in eliminating pure tones in the Point Lepreau study. Configurations 5, 6, 7 and 8 involve notched orifice openings with approximately the same loss coefficient as the standard orifice. Configurations 9 and 10 involve an orifice with an eccentric opening and multiple openings respectively. All configurations were tested for their ability to generate or eliminate pure tones.

3.0 DESCRIPTION OF TEST LOCATION AND MEASUREMENT TECHNIQUES

Six pressure transducers, P1 to P6, capable of high frequency measurements were used. They are arranged in 3 pairs, two along the '6-inch' piping upstream of the orifice under test and one along the downstream '16-inch' line. The pressure signals from each pair of transducers indicate the magnitude of pressure fluctuation, and can be used to calculate the net acoustic intensity which is the rate of flow of acoustic energy per unit cross sectional area of a pipe. The evaluation of net acoustic intensities both upstream and downstream of an orifice allow an assessment of the source and strength of excitation. A detailed description of this method is found in Reference 2.

The purposes of having two pairs of pressure transducers upstream of the orifice are, first, to enable accurate evaluation of sound speed which varies with operating conditions in the loop and, second, to determine the amount of acoustic energy transferred to the piping structure through the elbow immediately upstream of the orifice. The procedure for the evaluation of sound speed can also be found in Reference 2.

Four accelerometers, A1 to A4, were installed at the elbows of the loop. Each is oriented at 45 degrees on the outer radius of an elbow. The signals allow an assessment of the level of vibration and also detailed evaluation of the amount of excitation at each elbow by the acoustic pressure.

The above pressure and accelerometer signals were digitized, saved and analyzed (FFT frequency analysis) by a PC- based data acquisition system which is similar to that in Reference 2. Each spectrum in this report is typically averaged over 8 scans. The valid frequency range is 1 to 1000 Hz.

The flowrate through the loop was evaluated based on the differential pressure drop across two points on the loop as shown in Figure 1. This pressure drop was calibrated against the drop across the standard orifice (for which standard formulas are available for calculating flowrate) at different temperatures. Other quantities that were recorded include the loop temperature and the pressure drop across the orifice under test.

4.0 TEST PROCEDURE AND RESULTS

With the flow loop set up in each of the ten orifice configurations described in Section 2, measurements were obtained with various combinations of temperature and flowrate through the loop. The temperature typically was varied from 90 to 260°C in four steps. It was not feasible to maintain the temperature constant at lower temperatures due to limitations in cooling of the main pump loop. At each temperature, the flow was varied by adjusting the gate valve from typically 70 to 170 L/s through 5 to 8 steps.

The pressure at the discharge of the main pump was maintained constant at 8.9 MPa. There was no indication of cavitation in the loop throughout the tests.

The sound speed was determined from pressure measurements and is shown as a function of temperature in Figure 4. Its exact value actually also depends on local static pressure which in turn depends on the valve opening used to adjust the flowrate. However, the values in Figure 4 were considered sufficiently accurate for the purpose of this study and were used to evaluate the acoustic intensity in all tests.

Only the spectra of P3 and the acoustic intensity calculated from P3 and P4 for Configuration 1 are presented in the following discussions. These quantities can best be used to show the characteristics of a tone and the magnitude of the acoustic excitation. The results of other configurations are only discussed in comparison with Configuration 1.

An important aspect of this study is the observation of tones under various conditions, summarized in Figure 5. Each configuration is described by a plot of temperature versus frequency. An asterisk together with flowrate marks the presence of a tone. Also shown in the plots are lines which mark the frequencies at which the orifice is located at a pressure node of an acoustic mode. This figure is discussed below in conjunction with various orifice configurations.

4.1 Configuration 1 --- Standard Orifice at Reference Location

This configuration was originally tested and reported in Reference 1 to produce a pure tone at 512 Hz at a flow of 142 L/s and a temperature of around 80°C. In the present tests, a similar tone at 520 Hz was observed at a temperature of 90°C when the flow was at 119 L/s as shown in Figure 6. The 0-peak amplitude of the tone was 169 kPa. Other fluctuations at this temperature were generally below 10 kPa. The 300 Hz pressure fluctuation in this figure is the first harmonic of the blade-passing frequency of the main pump. The flow was not increased beyond 119 L/s to minimize operation at severe noise and vibration levels. Figures 7 and 8 show the acoustic intensity and acceleration (A2) spectra. The orders of magnitude increase in acoustic energy and vibration levels due to the tone is evident.

Figures 9 to 14 show pressure and acoustic intensity spectra at temperatures of 130, 220 and 260°C. It is seen that at these temperatures, the only tones present were those at 590 and 680 Hz, both occurring at 260°C (Figures 13 and 14). Upon repeating the tests on the next day, it was found that while the tone at 680 Hz reappeared under the same conditions, the tone at 590 Hz was absent. It is not clear what had changed between tests.

Discounting the contribution by pure tones, it can be seen that all the peaks in the acoustic intensity spectra (eg Figure 7) can be enveloped by sine curves whose peaks correspond to the lines in Figure 5. This means that the standard orifice is generating acoustic energy even when a tone is not present and this generation is at maximum when the orifice is located at a pressure node of an acoustic mode of the piping system. This is a situation of selective amplification of acoustic modes. It can be seen further from the proximity of asterisks to the lines that this condition also favours the generation of pure tones. This point will be better illustrated when the results for Configurations 2 to 4 are considered.

4.2 Configuration 2 --- Double Orifice at Reference Location

This configuration is recommended in Reference 1 as a solution to the elimination of pure tones and is again shown to be effective in the present tests. From acoustic intensity spectra, it was observed that the double orifice generates acoustic energy within the same range of frequencies as the standard orifice. But because it consists of two openings which cannot be located at a pressure node at the same time, pure tones are not generated. This orifice has a smaller pressure drop than the standard orifice as shown in Figure 15. This could also be a contributing factor towards the absence of tones.

4.3 Configuration 3 --- Standard Orifice Upstream of Reference Location

The effect of moving the orifice upstream is to selectively amplify acoustic modes with lower frequencies. This is seen as a shift of lines towards the left for this configuration compared with that for Configuration 1. Because of the shift in frequency, the 520 and 680 Hz tones in Configuration 1 did not re-appear while new tones at 280, 320 and 530 Hz appeared corresponding to the new position of the orifice.

4.4 Configuration 4 --- Standard Orifice Downstream of Reference Location

Compared with Configuration 1, the movement of the orifice in the downstream direction shifts the lines towards the right, strengthening (and slightly changing) the tone at 520 Hz and generating a new tone at 425 Hz. The tone at 680 Hz becomes weaker since the orifice is now farther away from a pressure node at that frequency.

4.5 Further Discussion of Results, Configurations 1 to 4

It is clear from all the observed tones that there are some preferred pure-tone frequencies irrespective of orifice location, such as the ones around 520 and 680 Hz. Apparently, these correspond to the mechanical resonant modes of the piping system. These modes are subject to acoustic excitation if fluid-structure interaction points are favourably located.

The interaction points include all flow discontinuities such as elbows, reducers, orifices and valves. The occurrence of a pure tone therefore requires a combination of mechanical resonance, location of an orifice at a pressure node, favourable interaction points and the 'right' type of orifice.

In a piping system typified by the Darlington Balance Line where the modal density is high, it is often not feasible to eliminate pure tones over the entire range of operating conditions simply by adjusting mechanical resonance or relocating orifices. This leaves modifying the orifice as a realistic option. The substitution of a standard orifice by a double orifice has been shown to be an effective solution. However, a modification of the configuration of the opening of a standard orifice, if proven to work, will be more economical. The remaining part of this study, Configurations 5 to 10 was carried out with that purpose in mind.

4.6 Configurations 5 and 6 --- Orifice with 16 Notches

This orifice has a slightly smaller circular opening than the standard orifice but has 16 equally-spaced notches around its opening so that the total opening area remains the same. This orifice was found to have the same pressure loss and general acoustic characteristics as the standard orifice except that a pure tone was not produced under any flow and temperature conditions. There were no tones with the orifice in positions corresponding to the Configurations 3 and 4 of the standard orifice. Two possible explanations for this success are: 1) the notches disturb the shear layer originating from the flow separation points of the orifice opening and reduce the rate of growth of acoustically excited instability waves within the shear layer; and/or 2) the notches disrupt the coherence of annular vortices formed around the opening of the orifice.

4.7 Configurations 7 and 8 --- Orifice with 2 and 4 Notches

These two configurations were used to determine the effect of the number of notches around the orifice opening on the generation of pure tones. The orifice was fixed at the same location as in Configuration 4. In Configuration 7, there are four notches and the results showed only a weak tone of 530 Hz at around 100°C with amplitude increasing with flowrate, reaching 25 kPa 0-peak at the maximum flow of 163 L/s. Pressure fluctuations under other conditions were typically under 10 kPa amplitude. In Configuration 8, there are only two notches, but the results were about the same as for Configuration 7 in terms of temperature and frequency, showing a maximum amplitude of 25 kPa at 140 L/s and 20 kPa at 158 L/s. From these two configurations, it seems that the tones produced by a standard orifice can be eliminated or weakened considerably by rather small 'imperfections' of the orifice opening.

4.8 Configuration 9 --- Orifice with Offset Opening

The orifice opening was offset in this configuration by 35.1 mm. A tone of 715 Hz with an amplitude of 70 kPa was produced only at 260°C and 159 L/s. The pressure loss across this orifice is approximately 20% less than that across the standard orifice as shown in Figure 15.

4.9 Configuration 10 --- Orifice with Multiple Opening

There are four openings in this orifice. No tone was observed under all conditions. It should be noted that the pressure loss across this orifice was only approximately 60% of that across the standard orifice although their total opening areas are the same. This shows that the effect of the thickness of the orifice plate becomes significant when the diameter of the holes is small. The absence of a tone could be due to the multiple opening or the reduction of pressure loss across the orifice.

4.10 Comparison with Darlington Results

Pressure and acoustic intensity measurements had been carried out on the balance lines of Darlington. Some typical results are shown in Figure 16. In Figure 16a where a tone is absent, it is seen that pressure peaks are spaced at regular intervals of approximately 13.3 Hz. This is indicative of the acoustic modes of the entire length of the line. From the total length of these lines (approximately 53 m between reactor outlet headers) and the above frequency interval, the wave speed is 1410 m/s. This is close to the expected value for water at low temperatures. It is also seen that the peaks in the acoustic intensity spectrum are enveloped approximately by a sine curve similar to that discussed in Section 4.1. When a tone is present, as shown in Figure 16b, the pressure fluctuation and acoustic intensity are orders of magnitude higher than their background values and are comparable to that observed in the present tests.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A parametric test has been carried out to determine the conditions under which an orifice can generate pure tones in a piping system. An existing flow loop was used, covering different orifice locations and a wide range of temperature, flowrate and orifice configurations.

It is found that in general an orifice is an acoustic source and produces a maximum flow of acoustic energy away from it for those acoustic modes that have pressure nodes located at or near the orifice. Those acoustic modes are selectively amplified by the orifice and can potentially develop into pure tones. A high level of vibration of the piping structure, however, requires that the natural frequency of a structural mode matches that of an acoustic mode, and the structural mode and acoustic mode are favourably coupled together through discontinuities (eg elbows).

Of all the orifices tested, only the standard orifice with a concentric circular opening gives a high level of pressure pulsation and vibration. Even a small deviation from the circular opening, in the form of two notches, can considerably reduce the occurrence or strength of pure tones. A novel orifice design with 16 notches was shown to be effective in eliminating pure tones under all conditions while retaining the same pressure loss.

It is recommended to replace the standard orifice with a notched orifice which provides an equivalent pressure drop wherever a pure tone related problem may exist.

The present study does not cover the effects of the size of the orifice opening. It is clear that for any piping system, the orifice opening can always be enlarged as a means to eliminate pure tones. However, enlarging the orifice will reduce the pressure drop, which may be unacceptable to the process.

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1. R.T. Hartlen and B.A. White, "Point Lepreau PHT Stability Line Orifice Tests", Ontario Hydro Research Report No 87-80-CON.

2. R. Ko, "Piping Vibration Evaluation System", Ontario Hydro Research Report No 87-180-K.

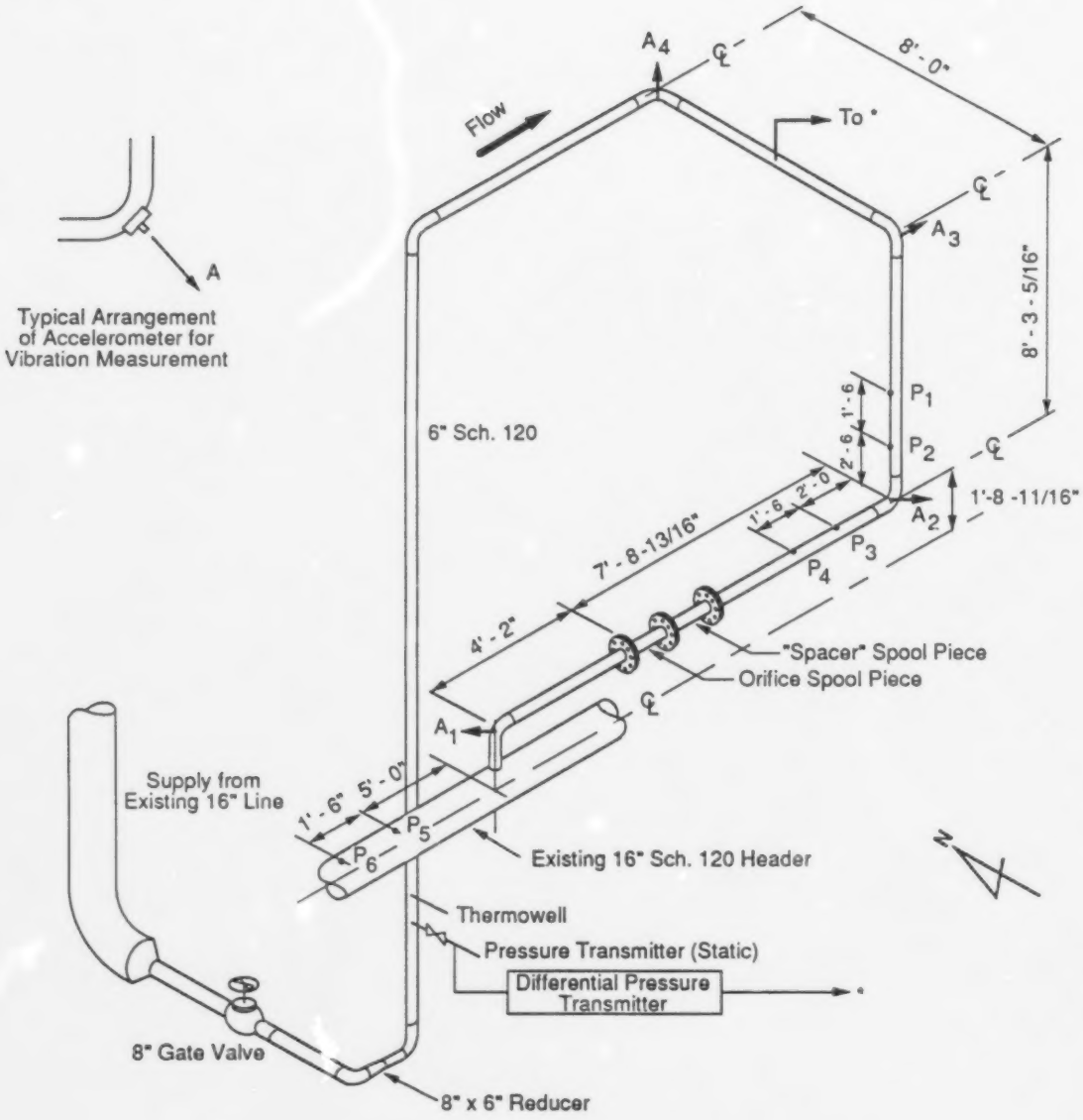

FIGURE 1

GENERAL LAYOUT OF FLOW LOOP

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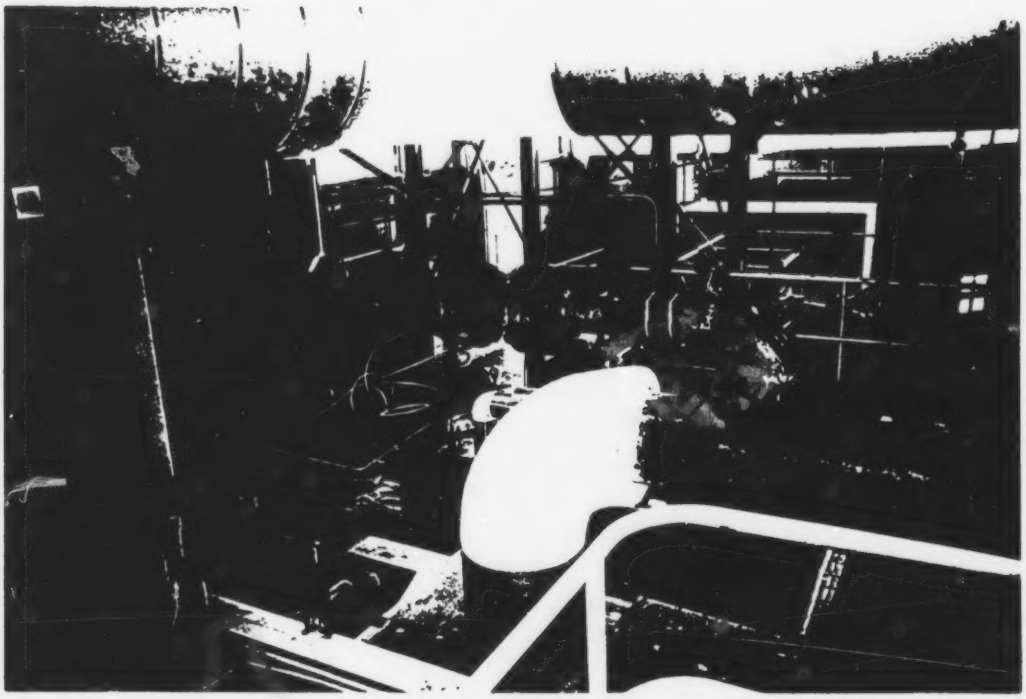
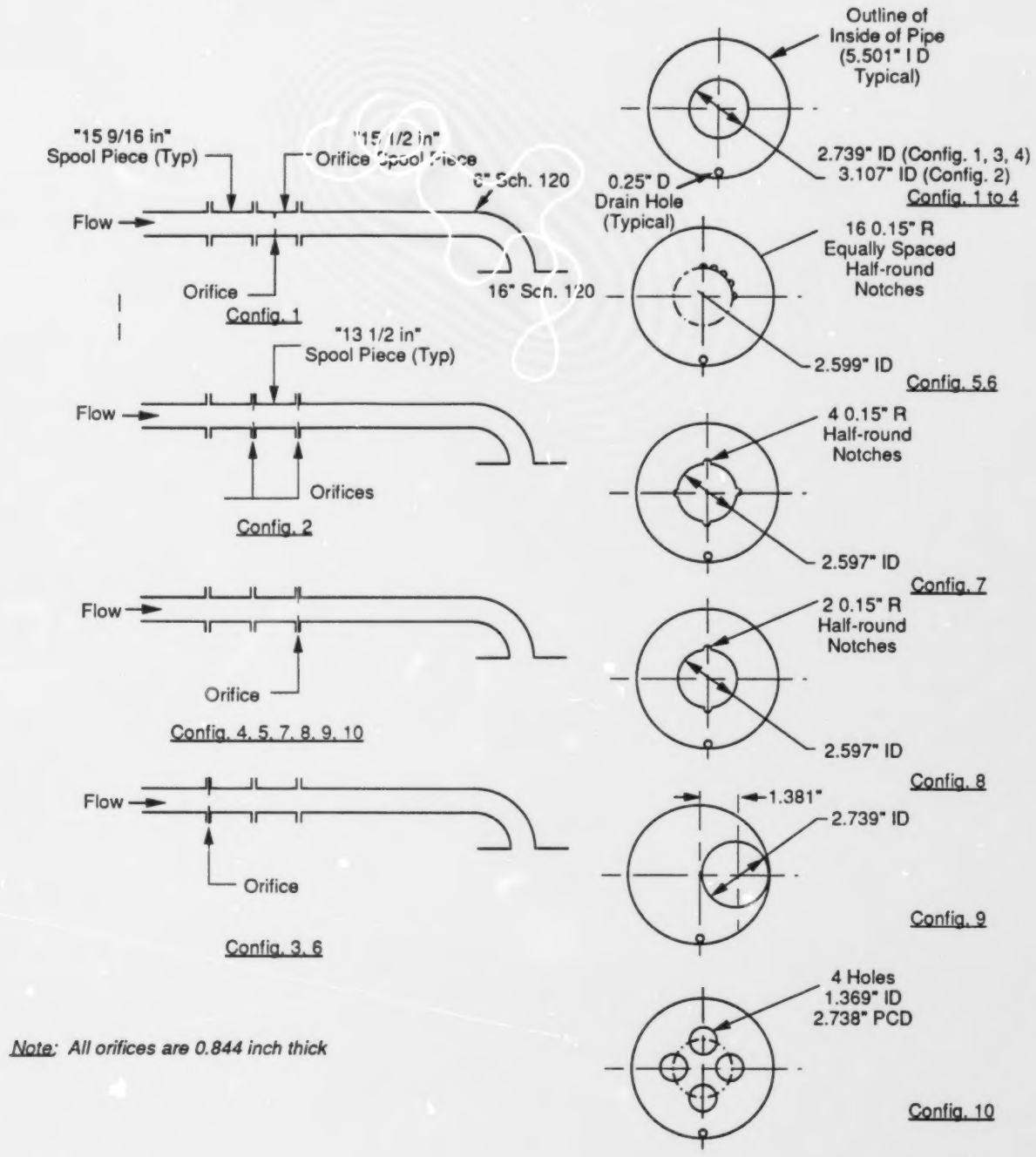


FIGURE 2

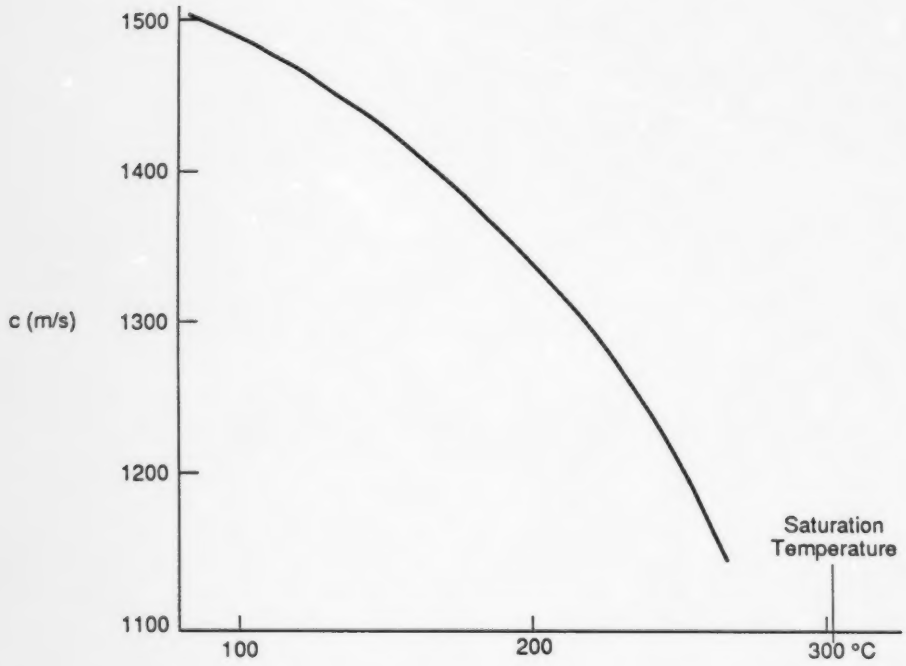
PICTURE OF FLOW LOOP AT ORIFICE LOCATION



Note: All orifices are 0.844 inch thick

FIGURE 3

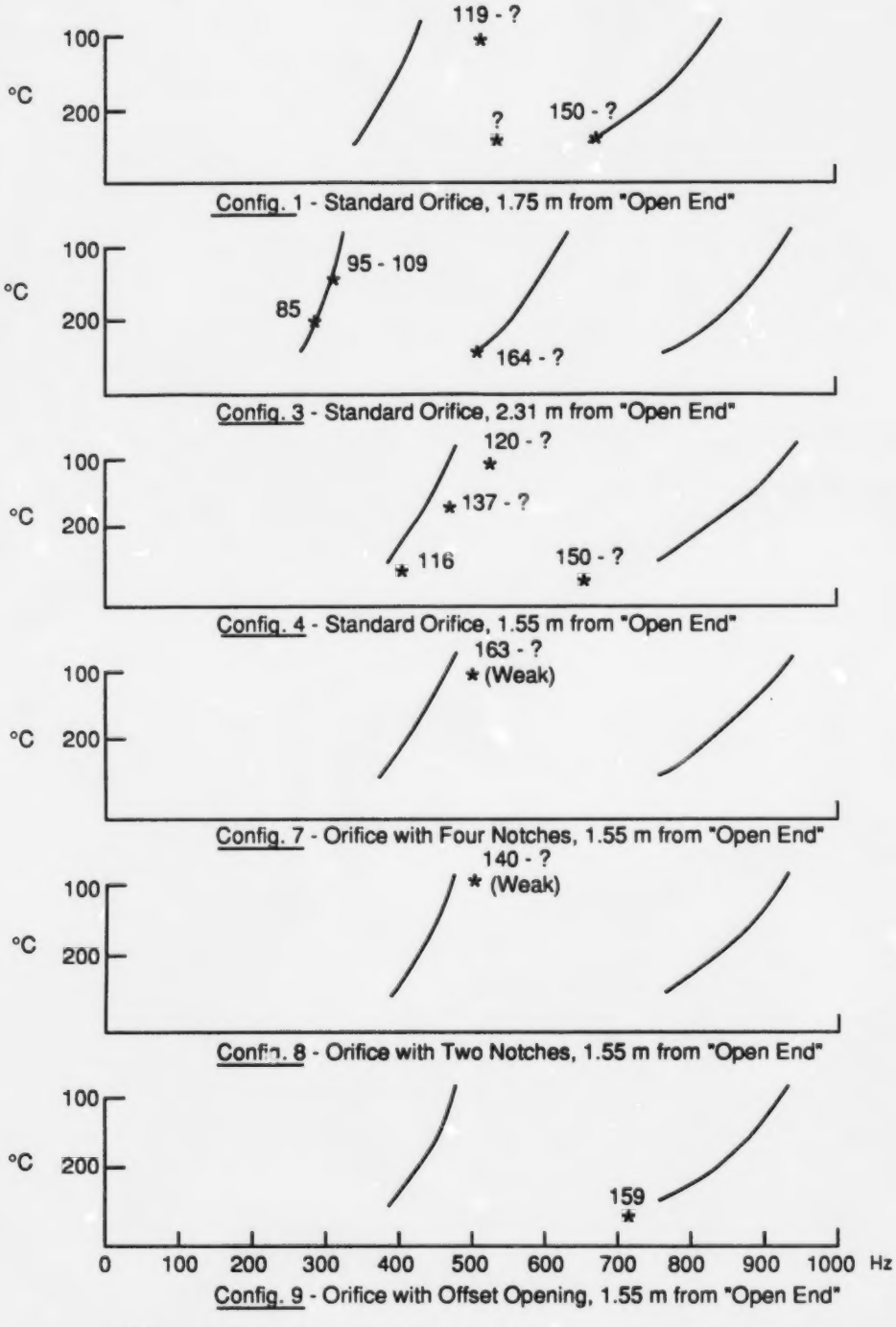
SUMMARY OF ORIFICE CONFIGURATIONS



Note: Static pressure at pump discharge = 8.9 MPa

FIGURE 4

VARIATION OF WAVE SPEED WITH TEMPERATURE



Note: Occurrences of pure tones are indicated by ★.
Numbers beside ★ indicate flowrate in L/s.
Curves indicate frequencies at which the orifice is situated at a pressure node of an acoustic mode.

FIGURE 5

SUMMARY OF PURE TONES OBSERVED UNDER VARIOUS CONDITIONS

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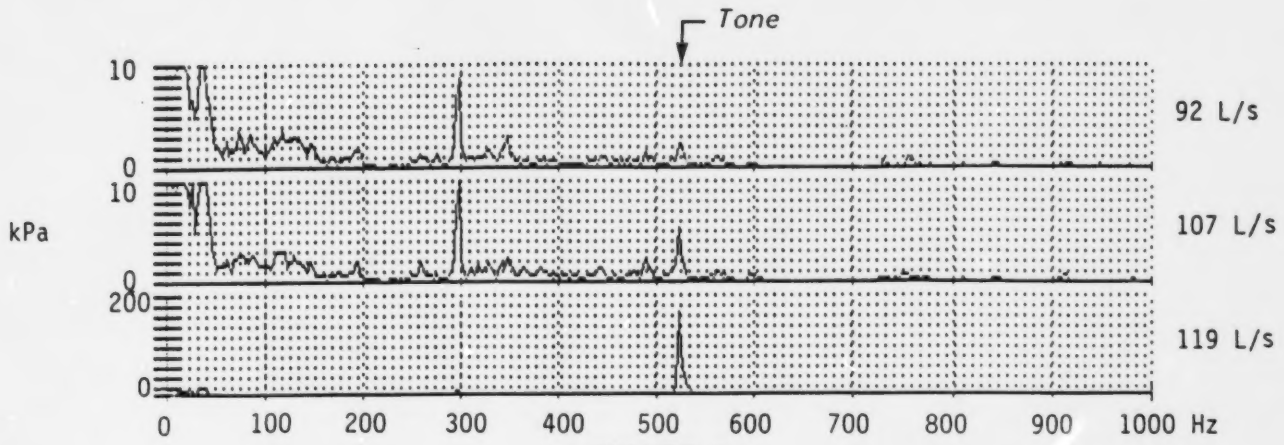


FIGURE 6

PRESSURE FLUCTUATION, CONFIG. 1, 90°C

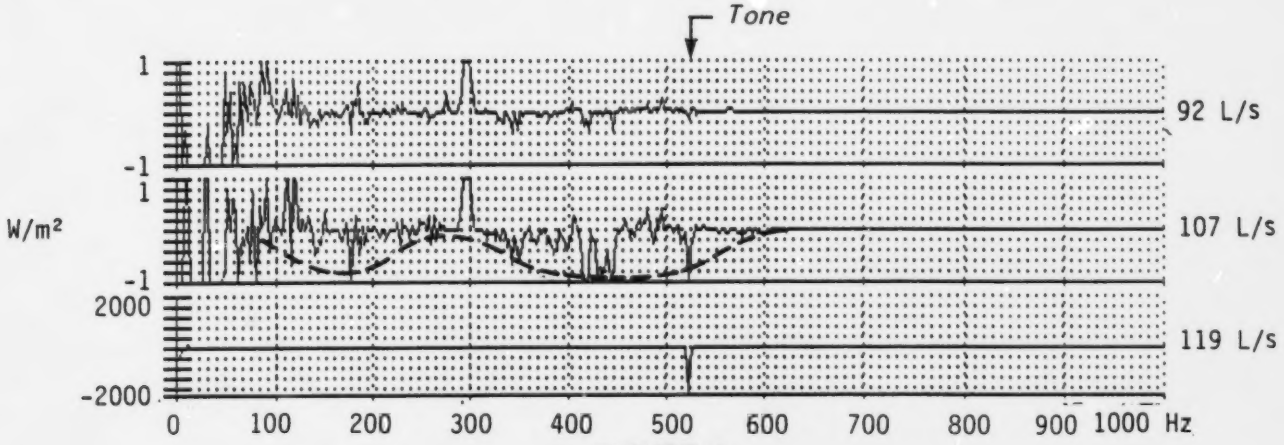


FIGURE 7

ACOUSTIC INTENSITY, CONFIG. 1, 90°C

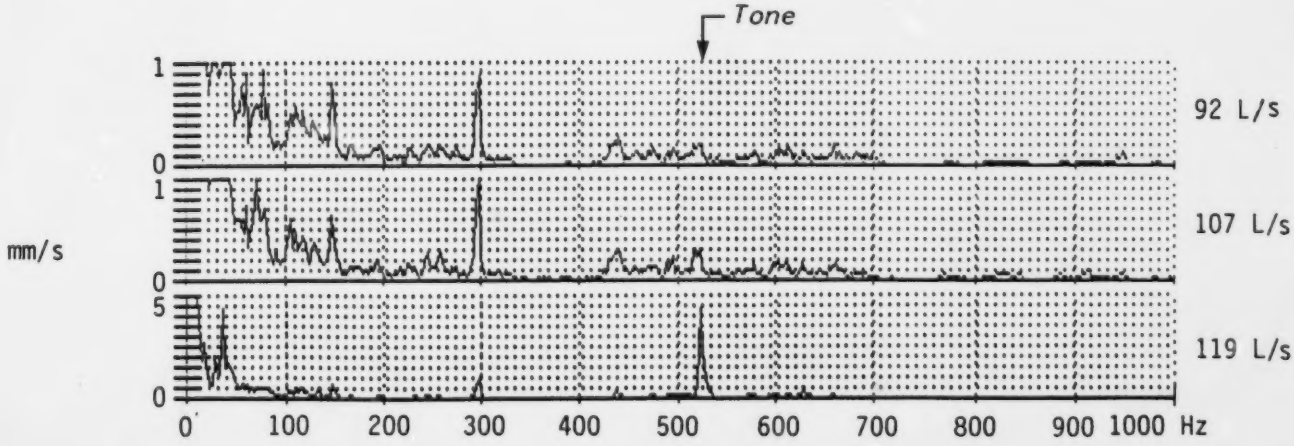


FIGURE 8

VIBRATION VELOCITY, CONFIG. 1, 90°C

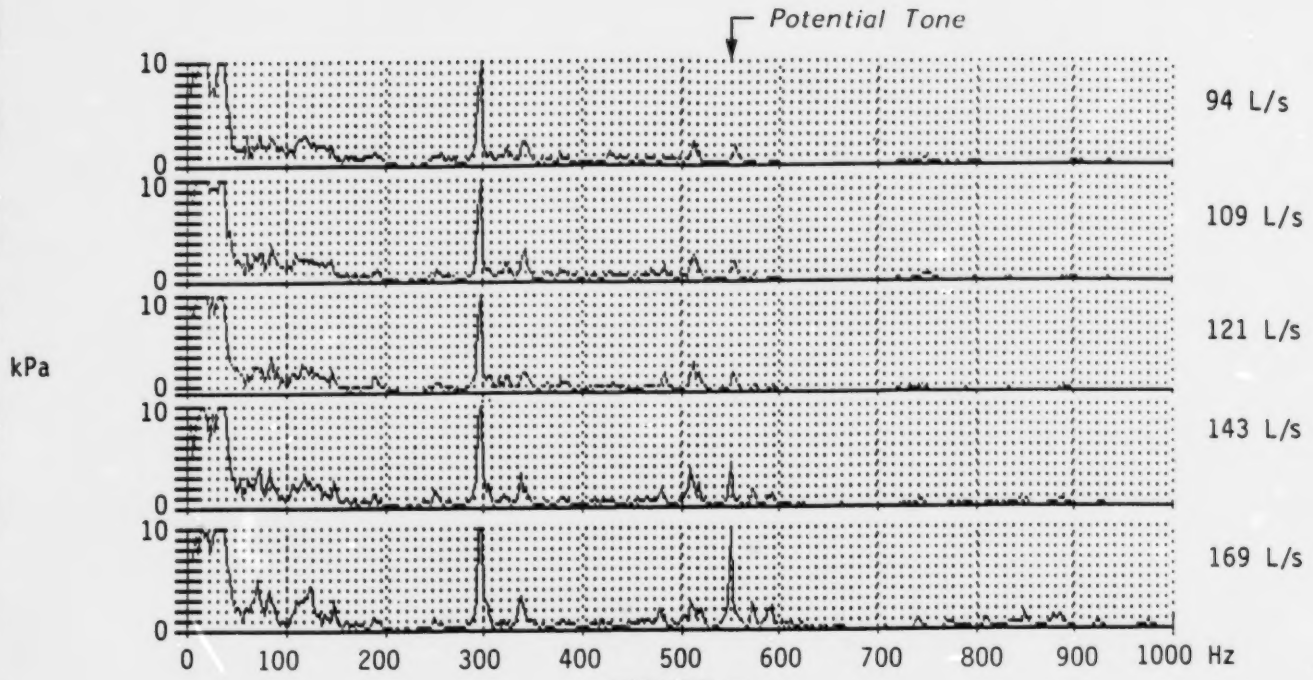


FIGURE 9

PRESSURE FLUCTUATION, CONFIG. 1, 130°C

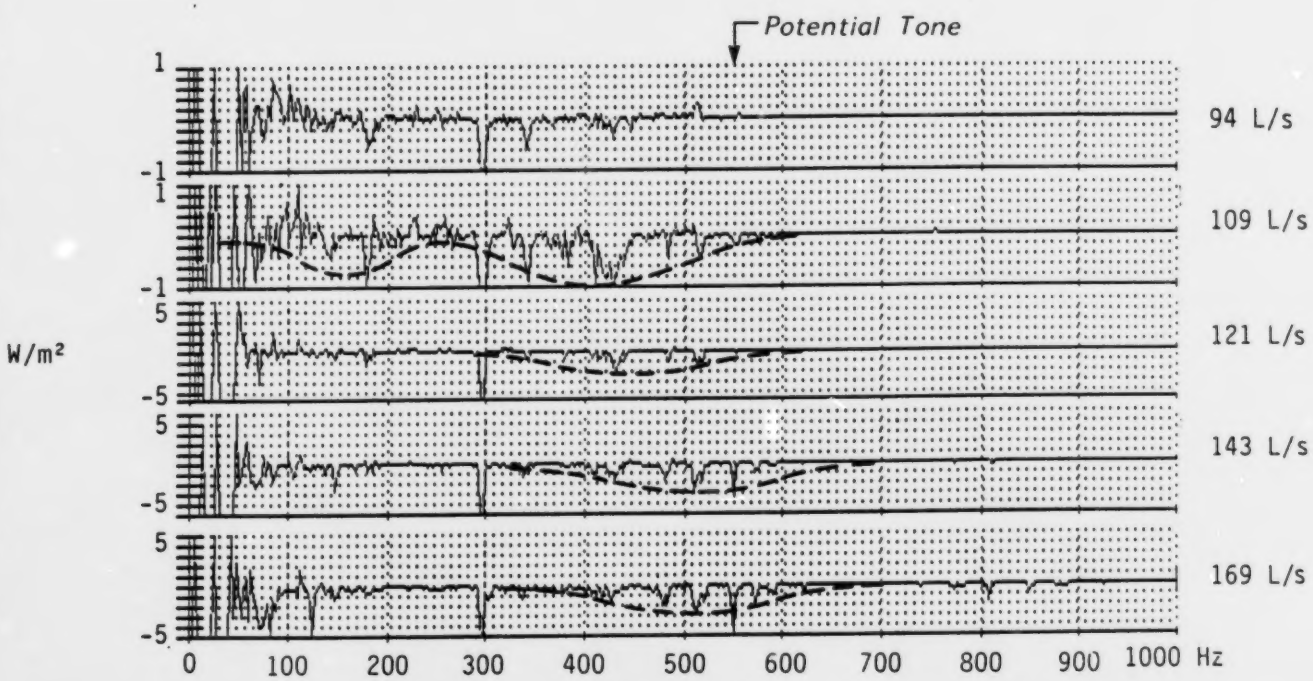


FIGURE 10

ACOUSTIC INTENSITY, CONFIG. 1, 130°C

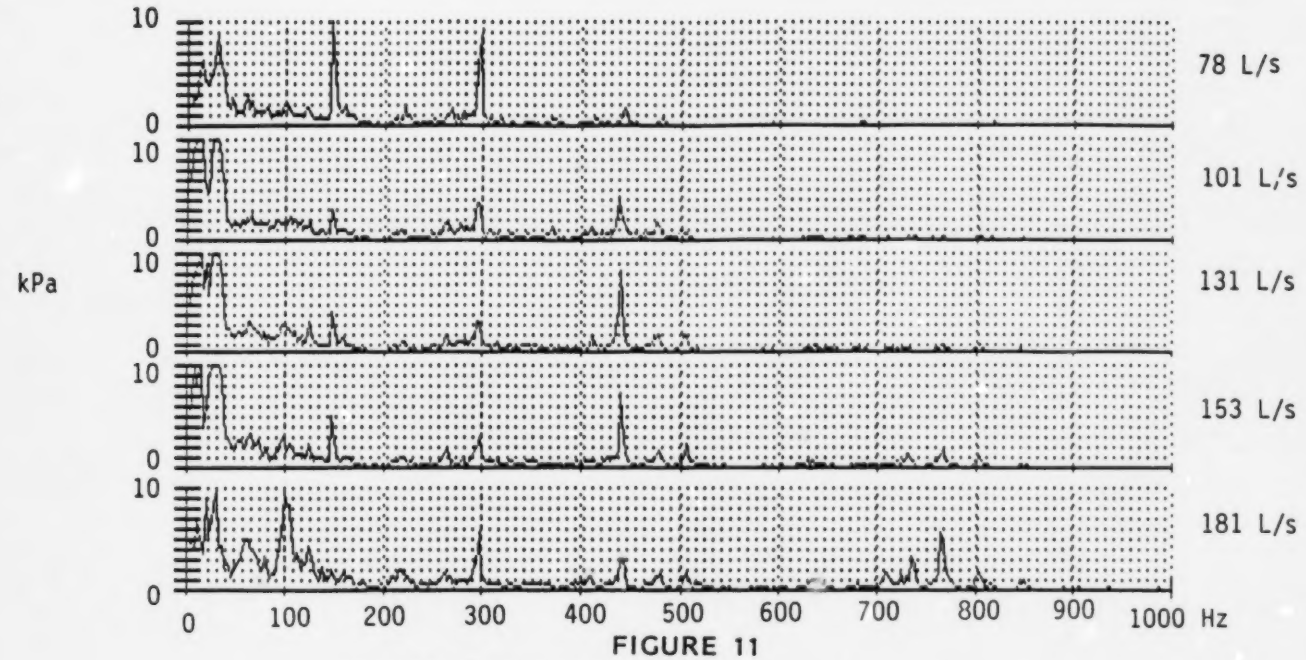


FIGURE 11

PRESSURE FLUCTUATION, CONFIG. 1, 220°C

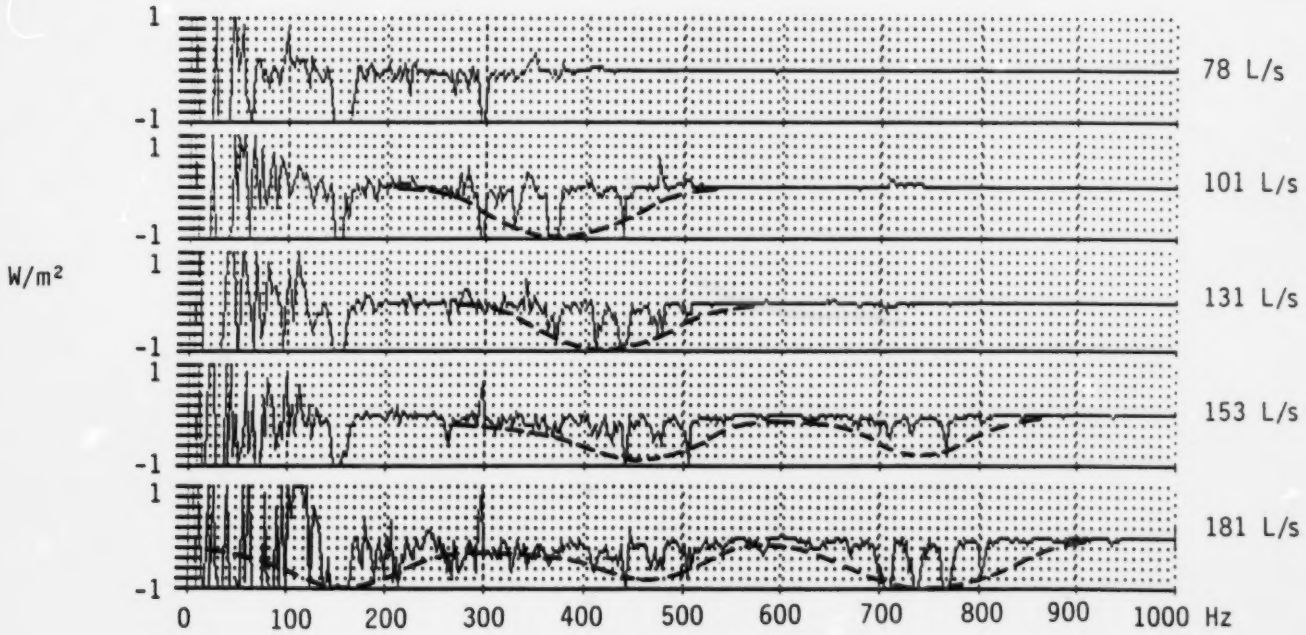


FIGURE 12

ACOUSTIC INTENSITY, CONFIG. 1, 220°C

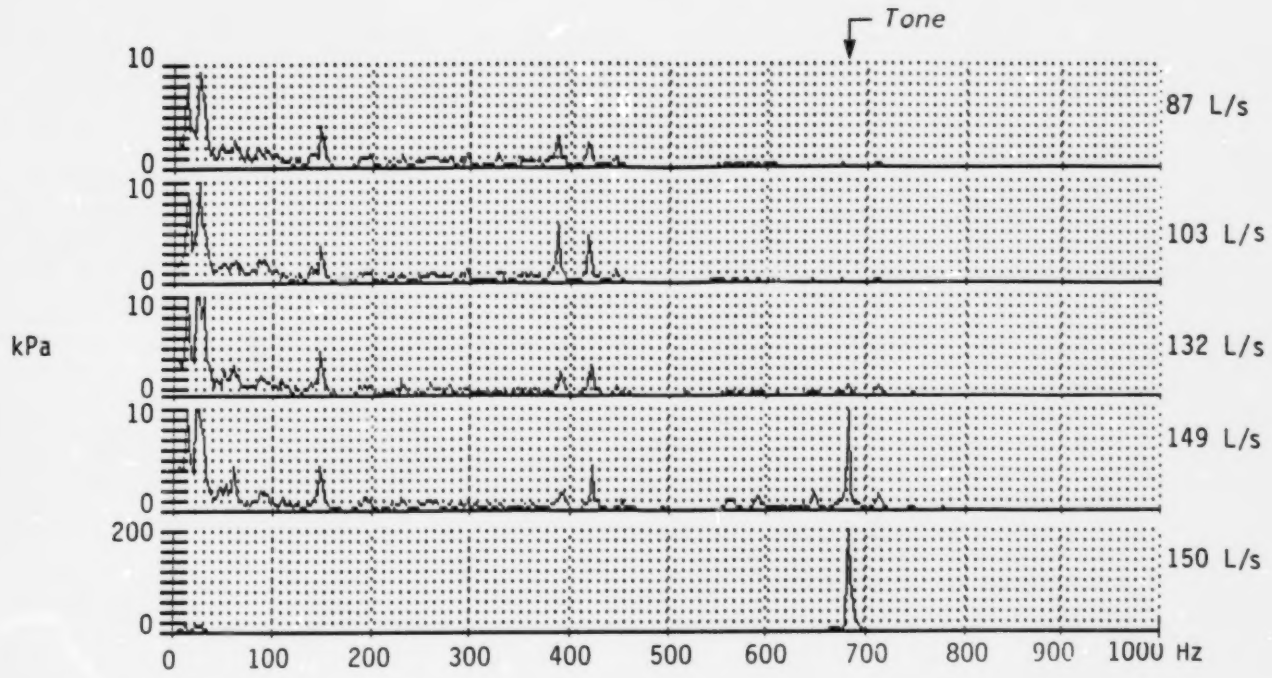


FIGURE 13
PRESSURE FLUCTUATION, CONFIG. 1, 260°C

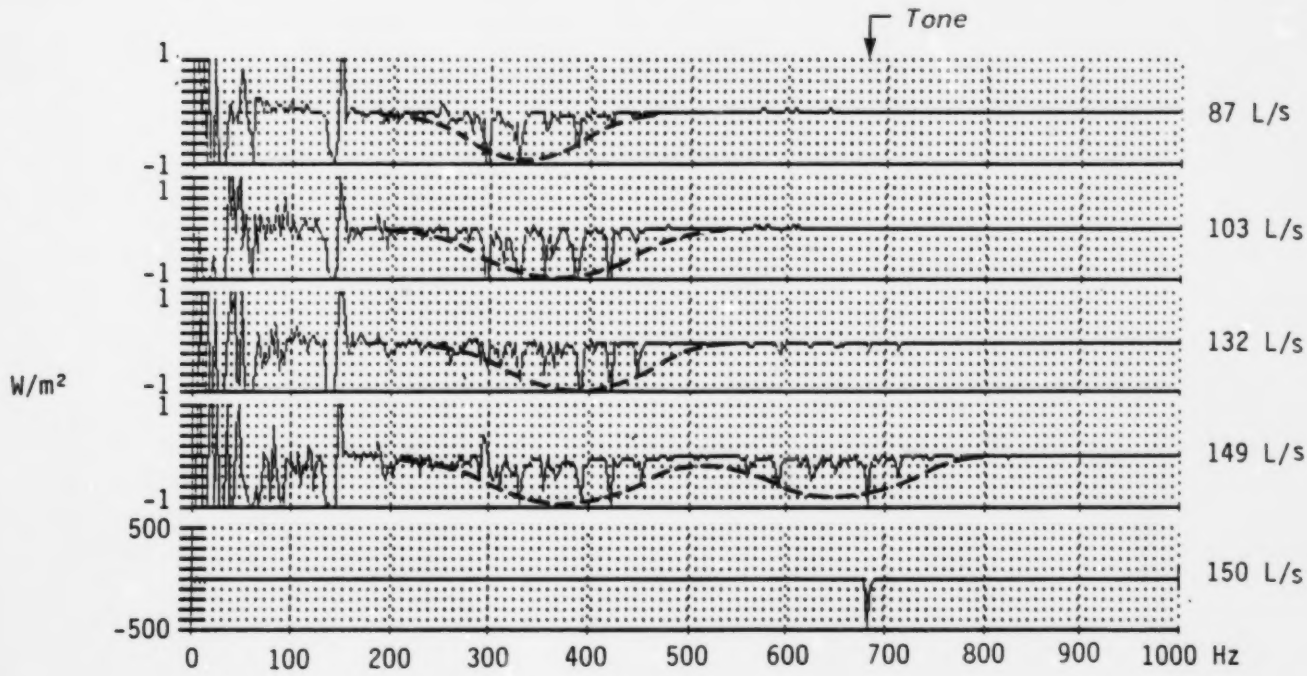


FIGURE 14
ACOUSTIC INTENSITY, CONFIG. 1, 260°C

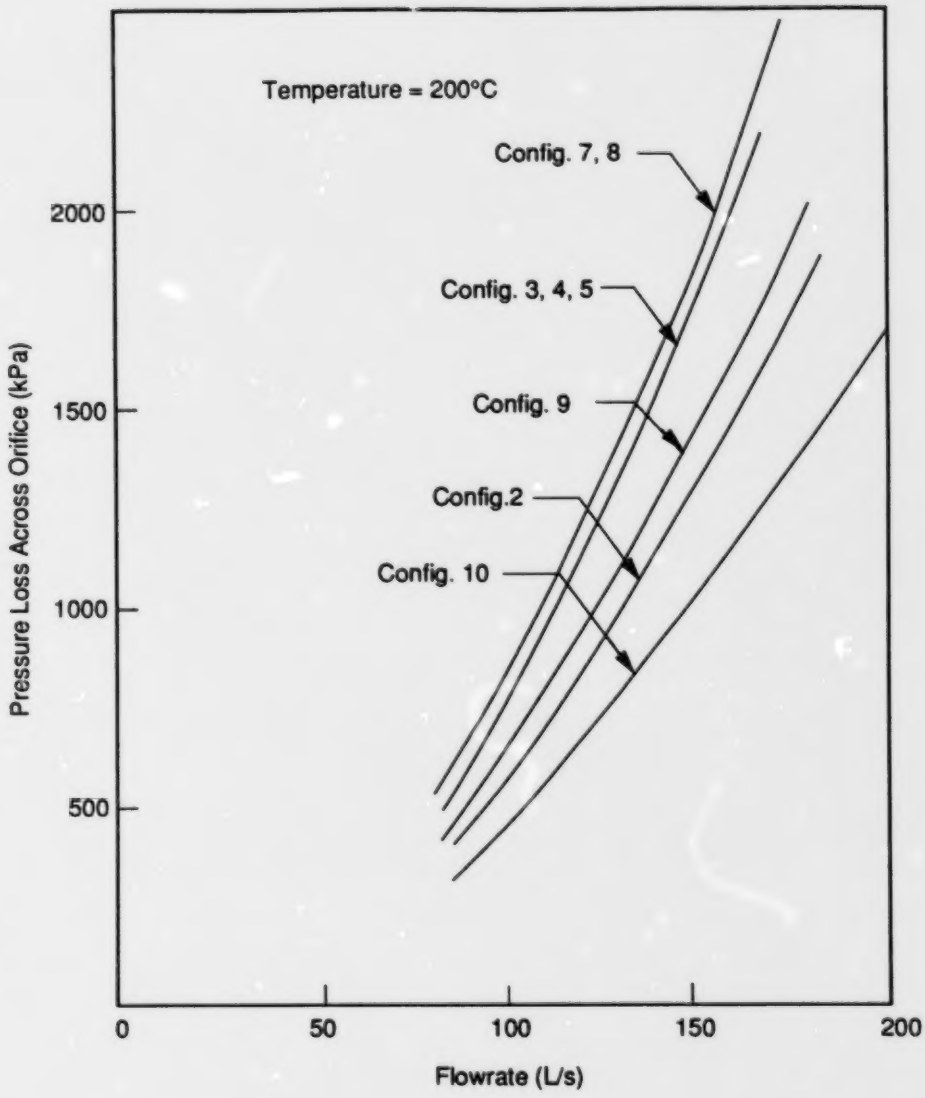
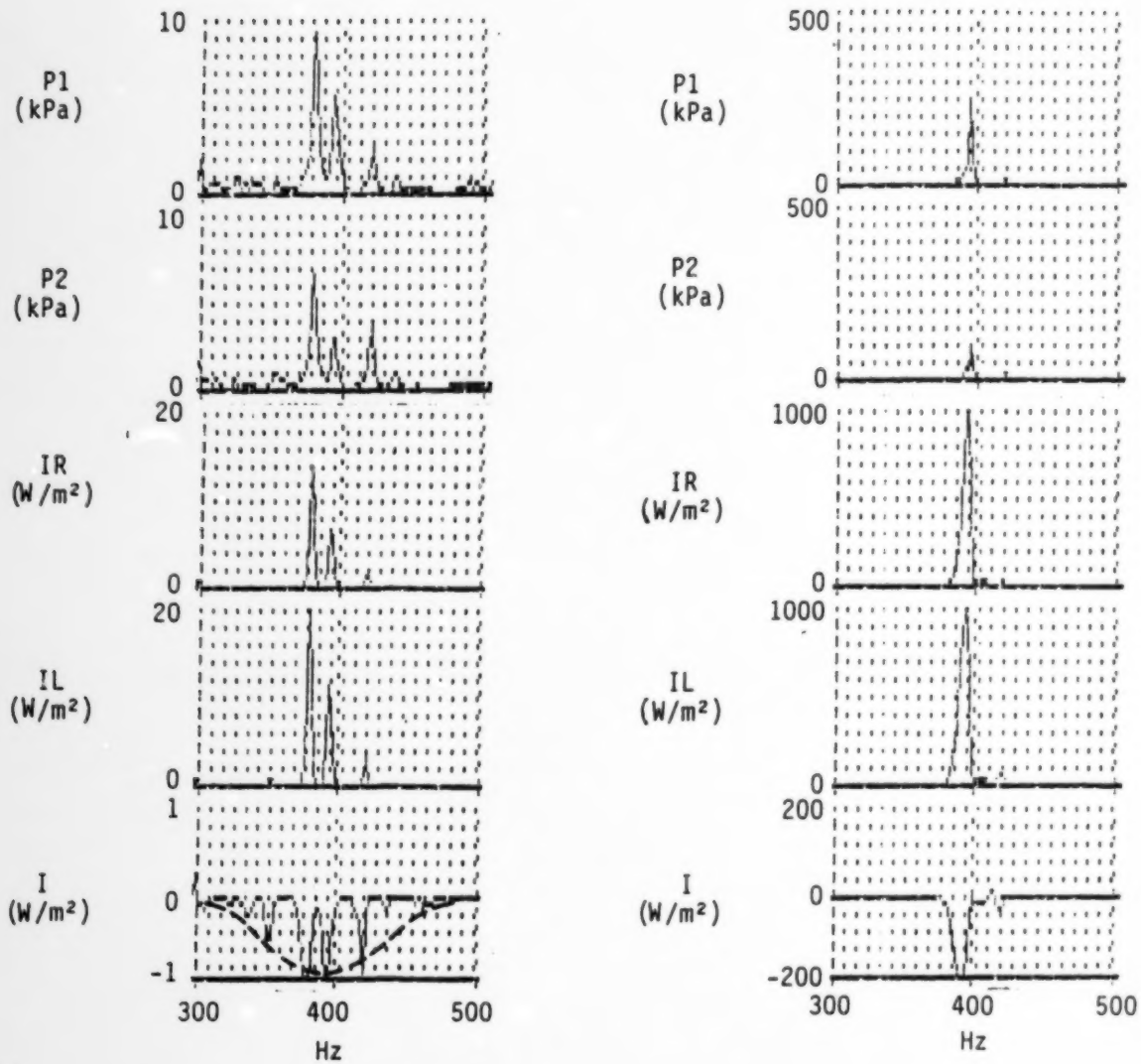


FIGURE 15

COMPARISON OF PRESSURE LOSS ACROSS ORIFICES



(a) No Tone

Pump 4 Operating
Pump 3 Turbining

(b) With Tone

Pump 4 Operating
Pump 3 Braked

From: *"Presentation on ROH Balance Line Vibration and Pressure Measurements Darlington NGS", June 1, 1988, Pages E-1, F-1.*

FIGURE 16
TYPICAL RESULTS FROM DARLINGTON BALANCES LINE L-31